Unique Systems Analysis Task 7, Advanced Subsonic Technologies Evaluation Analysis

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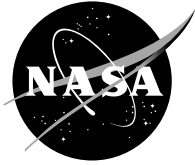
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National Aeronautics and
Space Administration

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Document History

This research was originally published internally as AST004 in December 1996.

Report Organization

This report has been organized such that Attachment A is a complete final report in a briefing type format, with appropriate information and detail to be a stand alone document (similar to the final briefing provided on Oct 7, 1994). This portion (main body) of this report is essentially a supplement to the attachment and contains an introduction, a list of acronym definitions and additional information for the reader desiring more supporting text to the "charts" of the attachment. The report is organized into 3 sections and the DOC guidelines provided by NASA are an included reference document.

Section 1   Executive Summary
Section 2   Technology Assessment Process
Section 3   Technology Evaluation & Engine/Cycle Selection
    3.1   Technology Impact on Engine
    3.2   Engine Cycle Analysis and Selection Process
    3.3   Selected Engines Assessment (Design, Materials, Weight)
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Document 1 -   Modified Direct Operating Cost Plus Interest Ground Rules for AST

Attachment A -   Final Report Briefing Format

List of Acronyms / Definitions

AST	Advanced Subsonic Technologies
ATEGG	Advanced Turbine Engine Gas Generator
BPR	Bypass Ratio
DOC	Direct Operating Cost
EFH	Engine Flight Hour
EIS	Entry Into Service
EMD	Engineering & Manufacturing Development
EPNdb	Effective Perceived Noise level in decibels
EPNL	Effective Perceived Noise Level
FAR	Federal Aviation Regulation
FN	Thrust
FN/Wgt	Thrust/Weight Ratio
FOM	Figure of Merit
FPR	Fan Pressure Ratio (generally referring to tip pressure ratio)
HP	High Pressure (as in compressor or turbine)
IRAD	Independent Research and Development
LDI	Lean Direct Injection
LP	Low Pressure (as in compressor or turbine)
MDA	McDonnell Douglas Aerospace
MDA-W	McDonnell Douglas Aerospace-West
MFB	Mission Fuel Burn
OMC	Organic Matrix Composite
OPR	Overall compression pressure ratio
PMC	Polymer Matrix Composite
R&D	Research and Development
RIT	Rotor (high pressure turbine) Inlet Temperature
SFC	Specific Fuel Consumption
TAD	Technology Availability Date
TiAl	Titanium Aluminide
Tm	Material Temperature (allowable)
TOGW	TakeOff Gross Weight

Discussion

Attachment A is in briefing format, similar to the final briefing provided on Oct 7, 1994, and has been organized as requested by NASA. The executive summary (Section 1) is a top level overview of the study program including a financial summary, a needs and problem (challenge) statement, the study objective and results of the study. It concludes with a list of the highest priority technology needs from Allison's perspective. Section 2, the Technology Assessment Process, is a description of the process used in the study to evaluate and select engine/cycle options and to quantify the benefits of the technologies under consideration. Section 3, Technology Evaluation and Engine/Cycle Selection, is the bulk of the report and is a description of the study process steps and results, from the identification of the candidate technologies, their impact on the engine, including noise and chemical emissions assessments, to the final selection of representative baseline and advanced technology engines and the resulting total and individual/incremental technology payoffs.

Section 1 - Executive Summary:

The executive summary (Figures A2-A12) is by definition a top level overview, therefore minimal additional text is provided. The summary can be stated in concise form by as follows:

- The program was completed on budget (Figure A3).
  General introductory information such as need statement, objectives, and how the program "fits" relative to the overall NASA AST Goals are presented in Figures A4-8.

- The application under study in it's final iteration was a 150 passenger, 2500 NM design range, regional, twin engine aircraft. This design range is consistent with a "typical" mission range of 500 NM.

- 25000-30000# thrust class, high bypass turbofans are the desired engines for this system.

- The payoff of "advanced" technologies consistent with a 2005 entry into service (EIS) system as compared to an optimized 1993 EIS technology baseline are significant and can be summarized as follows (see Figures A9-10):
  - Reduced System DOC (market based / delta-cost based)   ~2% / ~4.5%
  - Reduced Aircraft TOGW   ~8 %
  - Reduced Aircraft MFB   ~15%
  - Reduced Engine SFC   ~20% cruise
  - Reduced Engine Weight (with nacelle / engine only)   ~20% / 30%
  - Reduced Engine Length   ~20%
  - Reduced Engine Noise - satisfies goal of FAR-Part 36, Stage 3 less 6-7 EPNdb
  - Reduced Engine Emissions - satisfies goal of current ICAO less 70% (NOx)

A full complement of advanced technologies is summarized in Figure A-24 and materials are summarized in Figure A-39. The acquisition cost impacts as assessed for this study are summarized in Figure A-55, and maintenance cost impacts are summarized in Figure A-56. An overall technology impact summary is provided as Table 1 on page 21-22 and is summarized pictorially as Chart 1 on page 23.
The above improvements account for the impact of the engine only, not including aircraft improvements, which would contribute additional benefits.

- The technologies of highest priority from Allison's perspective are: (Figure A11)
    - Low Cost, Low Emissions Combustor
    - Affordable Advanced-Cooled High Pressure Turbine
    - High Temperature Seal Technology
    - Low Noise, Lightweight Fan System
    - Mature Analytical Models for High Efficiency, High Pressure Ratio Compressors

- The resulting 2005 EIS engine is a high design bypass (17.6 BPR) turbofan with a design overall pressure ratio (OPR) of 39 and a turbine rotor inlet temperature (RIT) of 2900 °F (new engine, max take-off rating) as shown on Figure A12.

Section 2 - Technology Assessment Process:

This section (Figures A13-A22) is a general description of the technology assessment process. The purpose of this section is to provide the reader with a general understanding of the evaluation approach whereas section 3 will describe the specific details.

The technology assessment process (Figures A14-A16) starts with defining study guidelines, such as application and timeframe. Then a list of candidate technologies is created, and screened, by selecting those items meeting the EIS guidelines. The sources of the technology candidates are other IHPTET related programs and planning activities, IRAD programs plans, and additional brainstorming.

Each of the technology candidates passing the initial screening, as indicated above, are first defined in terms of their impact on engine component's performance and weight (Figure A17). The technologies are then assessed in terms of production and maintenance cost impacts. These impact assessments may be updated at various stages of the study as more detailed analysis is conducted and lessons are learned, and these updates may require repeat iterations of some portions of the study process.

The next step is to define engine cycle modelling characteristics that represent "baseline" technology to serve as the reference of comparison for the study. Another "set" of engine cycle modelling characteristics are defined that represent an "advanced" technology level which includes the combined impacts of all of the initially selected/screened technologies. These modelling characteristics are represented in the form of component or system parameter relationships, such as efficiency levels, allowable metal temperatures, cooling effectiveness and secondary flow terms, pressure losses, etc. A study range or matrix of primary engine cycle (Brayton) parameters, such as turbine rotor inlet temperature (RIT), overall pressure ratio (OPR), and fan pressure ratio (FPR) are also defined for both the baseline and advanced technology levels (Figure A18).

The above matrix of engine cycle cases is run in a simulation program ("TERMAP") to generate characteristics such as fuel consumption and specific thrust. A rough initial estimate of weights is established for each engine of the cycle matrix, thus thrust-to-weight characteristics can also be generated for the engines. From this information a baseline engine cycle and one or more advanced engine cycles are selected as initial candidates to undergo more detailed analyses (Figure A19), including emissions assessments, secondary flow system sizing, and a preliminary

(mechanical) design of sufficient depth to generate cross-sections, installation drawings, and detailed weight assessments. Ultimately these analyses serve as a means to generate relationships and trends to refine the assumptions used in the engine/cycle parametric study and thus to calibrate the model. This updated model will then be used to repeat the parametric analysis and select the final engine cycles to represent the "chosen" baseline and advanced engines.

In the meantime a representative initial study aircraft is defined (general configuration, weight and drag characteristics) along with a mission objective (Figure A20). This information is used in combination with one of the initial engine candidates as input to an aircraft and mission optimization analysis. The result of this "aircraft mission analysis" is a set of relationships or "sensitivities" of aircraft takeoff gross weight (TOGW) and mission fuel burn (MFB) to engine SFC and FN/Wgt.

Another major element of the aircraft "system" assessment is the direct operating cost (DOC) analysis, and again this is generated in the form of a sensitivity to engine (and airplane) parameters such as fuel consumption, weight, acquisition cost, and maintenance cost.

Once a "final" baseline and advanced technology engine are selected, then the incremental (and thus individual) technology impacts on the overall system are assessed. This is accomplished by a number of incremental steps. At each step, starting with the baseline engine, a technology is added to the previous step, a complete parametric evaluation is conducted and an "optimum" engine solution is selected. The process continues until all technologies are incorporated which yields the advanced engine. Conceptually the technology assessment can be viewed in summary form as shown on Figure A21. Each technology under consideration has an impact at the engine component level, including performance, weight, and cost, which translates to overall engine fuel consumption, thrust/weight, emissions, and cost. This in turn impacts the aircraft TOGW, MFB, and costs, which in combination with many other system cost factors leads to a DOC impact. A separate, yet related task is a technology risk assessment, in which the technologies are evaluated in terms of relative risk. Highly structured risk assessment techniques play a significant role in development programs, after the technologies are better quantified in terms of cost and manufacturing impact, and those subsequent impacts on the program cost and schedule are also understood. For this type of future system conceptual study the risk assessment is simplified, as discussed in Section 3, since the technologies selected for evaluation meet certain guidelines by definition, such as technology availability date. Inherent in that decision is the assumption that the technology will be incorporated in such a way that the system life/durability requirements are met, and the technology can be developed by a given timeframe. Thus, by definition there should be no excessive risk technologies considered beyond the initial screening and selected for evaluation.

Perhaps a better visual way to summarize the study results is as shown on Figure A22. This figure summarizes the baseline and advanced technology engine cycle parametric study, shows the selected engines and displays incrementally each technology step of the "improvement path" from the selected baseline engine to the selected advanced engine. Note that the point representing each step along the improvement path is a "selected optimum" point out of a parametric family of curves (as is shown for the base and advanced engines).

Section 3 - Technology Evaluation & Engine/Cycle Selections:

Section 2 provided a general discussion of the technology assessment process. This section elaborates on the elements of that process as conducted for this study. Per customer (NASA) guidelines the timeframe for advanced technology candidates is consistent with 2005 EIS. This translates to a 2000-2001 technology availability date (TAD) and thus implies that technology candidates are currently (or will be within the next year or so) in a demonstration phase within the industry.

Figure A24 displays, in summary, the full compliment of advanced technologies, resulting from the initial screening process. These technologies addressed various engine improvements such as component efficiency and loading, secondary flows, materials for higher strength or temperature capability and/or reduced weight, and chemical and acoustic emissions.

The engine cycle evaluation process (Figure A25) starts with defining the technology levels for the baseline and the advanced configurations, in terms of component and cycle parameter impacts and relationships. It is actually an iterative process whereby an initial set of assumptions are used, then reasonably representative cycles are selected and analyzed, and then the component and technology level representations are updated. This process or various portions of it may take a few iterations to settle out. An interim iteration for this study led to the selection of one baseline and two advanced engine cycles (referred to as PD577-1A2, -2A2, and -3A2 respectively) which went through a fairly detailed level of analyses and preliminary mechanical design. The component and technology level representations presented herein are primarily the result of those analyses.

3.1 Technology Impact on the Engine

A summary of the net impacts of the advanced technology "package" is shown on Figure A26. The actual impacts as applied to the engine model are provided in the form of cycle parameter relationships or component weight changes in the weight estimating tool. The compressor, for example, is a relationship of efficiency to size and loading, or average pressure ratio per stage (Figure A27). Similar efficiency relationships are established for all rotating components (Figure A27-28). Since the fan is a single stage it is simply represented by efficiency versus pressure ratio. Several advances in the turbomachinery aero design contribute to performance/efficiency improvement projected for the timeframe of this study. As shown on Figure A24, these technologies include clearance control, secondary flow management, cooling flow mixing, blade/vane interaction, stage matching, and other advanced 3-D analyses. All considered the potential improvements were worth approximately +1 point in efficiency for each of the rotating components. Instead of attempting to quote accuracies beyond the capability of the analyses, a +1 point efficiency improvement was used "across the board" to represent the advanced technology level of component efficiencies. The NASA AST program guidelines had quoted a goal of +2 points, which was initially used for this study, but upon our investigation of potential improvements in the timeframe for this study, it was our assessment that more than +1 point was unrealistic. Although we are in agreement for maintaining high goals to target development efforts, we also wanted the engine cycle analysis to reflect a realistic projection of what would be attained, within "reasonable" risk.

Turbine airfoil cooling representation was initially an iterative process, in itself, and was analyzed with various technology level assumptions. A detailed cooling flow analysis was conducted on engine cycles PD577-1A2, -2A2, and -3A2 referenced above, based on defined

cooling technologies and materials as used in Allison's AE101 turbine. Figure A-29 is a display of advanced turbine airfoil cooling technology trends. It shows several levels of cooling effectiveness (φ) versus a cooling flow function (ϖ). φ is a function of the relative temperatures of the gaspath, the metal (airfoil) and the coolant. ϖ is a function of the cooling flow, specific heat, heat transfer coefficient, and surface area. The highest effectiveness level curve shown on the figure represents the theoretical potential (limit) of transpiration cooling. The next level shown is what Allison has achieved with a flat plate test specimen of 3-ply Lamilloy®. The next level is what Allison has demonstrated on it's ATEGG demonstrator (IHPTET Gen 5/6) turbine airfoils with a Lamilloy® fabrication, and is the level projected for fully developed Castcool® (a one-piece casting Lamilloy® airfoil) consistent with the advanced technology timeframe for this study. The next level shown in the figure is that of the Allison AE101 Lamilloy® turbine, as referenced above, and represents the baseline technology for this study.

Cooling flow requirements are evaluated for each airfoil in the hot section, then the total cooling flow requirements are summed up and represented in another similar cooling flow curve as shown on Figure A-30. This figure represents the total chargeable cooling flow plotted against a cooling function (similar to the effectiveness term of Figure A-29) which is stated in terms of turbine entry and cooling source conditions readily available in the cycle analyses (turbine rotor inlet temperature - RIT and compressor discharge temperature - CDT), and an input metal temperature (Tm-representative of the turbine first stage bulk average allowable metal temperature at approximately 30ksi and 12000 hours life). This method has been used very successfully for other similar studies. The figure shows the baseline and the advanced cooling technology level. At lower turbine inlet temperatures (with resulting cooling function values of approximately 0.5 or less) the difference between the baseline and advanced cooling requirements are relatively small, but as the cooling function rises above about 0.5 the advanced cooling scheme has a significant impact on required cooling levels. Furthermore as improved capability materials are introduced in the hot section (increased allowable metal temperature-Tm) the cooling function is driven to lower values resulting in reduced cooling requirements. For the advanced engine selected in this study the cooling function value was approximately 0.7.

Another technology which is also a contributor to the reduction of secondary flows in the engine is in the area of advanced seals. A recent Allison contract with NASA addressed specifically this subject matter (see Figure A-31). The results of that study showed a significant secondary flow reduction potential for various seal types and seal locations. The greatest impact was in two seal locations in the HP and LP turbine's disk front cavity by utilizing a circumferential film riding rim seal located near the cavity/flowpath interface. To further take advantage of the seal potential a dual property HP turbine wheel was incorporated , which has improved rim strength and allows increased operating rim temperatures. Translated to this study the benefit of those two seal locations alone are worth about a two point reduction in the secondary flow out of a total of approximately 4.5 points. This is the level of reduction that was used in this study to represent the advanced seal technology.

Figure A-32 represents the combined impact of the cooling and seal technologies, showing the total chargeable cooling flow which includes purge and leakage flows plotted as a function of the cooling function described previously. Also shown on the chart are typical values for allowable metal temperatures (for approximately 30ksi and 12000 hours life) for various modern and advanced materials. For this study single crystal CMSX3 was the baseline and a third

generation single crystal, CMSX10, was the advanced technology. In summary this single figure represents four technology items; the fully developed Castcool®/Lamilloy®, the circumferential rim seals in combination with the dual property HP turbine wheel, and the third generation single crystal single crystal material turbine airfoils.

Several other technologies are advanced material items, such as organic, or polymer matrix composites (OMC or PMC), metal matrix composites (MMC), and gamma titanium aluminides (γTiAl), as previously shown on Figure A-24. These technologies all represent weight reduction improvements for various components throughout the engine which is represented in the weight assessment tool.

The intent of this study was to focus on the core engine system, and thus it was considered outside of the scope of the study to investigate in any detail the nacelle improvement technologies. However it was also felt that some assessment was necessary to appropriately reflect the anticipated drag (and weight) of an advanced nacelle. Consultation with other nacelle designers and manufacturers and research of various reports and periodicals showed that significant low drag nacelle technologies are currently being investigated and incorporated with positive results. Laminar flow concepts and devices with an assessed technology availability timeframe consistent with a year 2005 EIS (the advanced technology level for this study) result in an overall nacelle drag reduction in the order of about 30%. Thus for this study the advanced technology engines have an assumed nacelle drag that is 70% of the nacelle drag calculations as used for the baseline. This improvement is however accompanied by a weight penalty estimated at about 5% of the nacelle weight.

Two other technology items, the low emissions combustor and the low noise fan are necessary technology items to attain the emissions goals for the study, but they do not impact engine cycle performance (power generation or fuel consumption) directly. They will be discussed in more detail in a later section.

The technology item descriptions and their impact discussed above were focused on engine performance and weight. A separate section (DOC Assessment) later in this report will discuss the other impacts of those technologies, such as acquisition and maintenance costs.

3.2 Engine Cycle Analyses and Selection Process

As mentioned earlier, all the technologies above and their impacts were combined together to represent an overall advanced technology package. An engine cycle parametric study was conducted for the two different technology levels (baseline and the advanced). Figures A-33 thru A-37 are representative of the types of characteristics that were generated for those parametric studies. These figures display the relationship of key parameters such as thrust (Fn), specific fuel consumption (SFC), bypass ratio (BPR), overall engine pressure ratio (OPR), fan pressure ratio (FPR), and turbine rotor inlet temperature (RIT). They provide a clear indication of the significant difference and improvement of the advanced technology level, as well as showing where the engine cycle optimizes, that is, the selected key parameters of RIT, OPR, FPR, and the resulting BPR that yields an optimum. For the exception of Figure A-34, these sample set of figures represent a fan pressure ratio of 1.4. The study considered a range of FPR from 1.2 to over 2.0. As will be discussed later the 1.4 FPR was chosen as an optimum compromise between engine performance and fan noise level.

Note that the discussion above relates to performance, but does not account for weight and cost analyses, nor does it account for mission analyses and "system" impacts, which are also parallel steps in the process and will be discussed later in this report. To start those evaluations cycles must be selected to analyze in more detail, and that selection must be made prior to cost and mission analysis information being available (for a first iteration). Allison had, of course, conducted studies of similar nature previously and has some experience from those studies results. Also previous studies have indicated a level of core compressor performance (and configuration) requirements for future systems. As a result Allison already had two advanced compression system data bases from which to draw to help support this study, as well as our baseline T406 core compressor (as developed for the T406 V22 application, the AE2100, and the AE3000 series engine family). During early iterations of the study parametric we also conducted a parametric around those core compressors. This also provided a good opportunity to evaluate the effect of fan pressure ratio for given core compressors as shown in Figure A-34. It turned out that 1.4 FPR, for any given core compressor pressure ratio, and regardless of technology level, appeared to be near optimum for minimum fuel consumption. This was a separate analysis from that which showed a FPR of 1.4 to be the highest desirable for noise considerations (discussed later in this report). The combination of the 1.4 FPR and the defined core compressors led to the definition of engine cycles PD577-1A as a baseline and -2A and -3A as advanced options. These cycle points are spotted on the remaining curves throughout the study, and represented a good point of departure for further detailed analyses of engine candidates. These three interim selected cycles provided us a baseline very near the optimum of the parametric and two options of an advanced technology engine, one being very near the optimum (-2A) and the other being a more conservative solution to an advanced engine cycle (-3A), not as optimum as the -2A but certainly still with a significant advantage over the baseline. The -1A resulted in an overall cycle pressure ratio just over 20 with a turbine rotor inlet temperature (RIT) of 2400°F. The -2A (the advanced cycle near optimum) had an OPR closer to 40 and an RIT of 2900°F, and the more conservative advanced cycle (-3A) had an OPR just above 25 and an RIT of 2700°F. This was a good interim set of solutions to cover the range of likely candidates to be ultimately decided later in the study process. Furthermore it represented core compressors, or scales thereof, that Allison had design experience with, thus gave improved validity and accuracy to the mechanical design and weight analysis.

3.3 Selected Engines Assessment

It should be noted, once again, that the cycles/engines discussed in this section represented an interim point of departure from which further detailed analysis was conducted to develop trends, characteristics and relationships that were utilized to update and refine the cycle model. Then the parametric assessment was subsequently repeated and final optimum cycle selections were made. In other words, the analyses described in this section provided a calibration of the cycle parametric analyses, configuration definition, and weight assessment processes for subsequent iterations.

Figure A-38 summarizes the type of analysis that was conducted on the three interim selected engines. A complete flowpath aero analysis was conducted to define the flowpath and the blade/vane count and volumes for blade pull stresses, etc. Wheel sizing was done for blade pull in all turbine and core compressor wheels, and for blade pull and dynamic stresses in the fan. The secondary flowpath and cooling requirements analysis was conducted at a detailed level.

The static structure was essentially scaled from other design experience, such as the AE3007 and AE3012. The fan drive gear reduction systems were specifically designed (at a PD level) for this study. All of this mechanical design was done at a level appropriate to define weights and general configuration. For example, when disk volumes were reasonably accurate, further iteration for disk shapes were discontinued. Material selections were made for all of the components of the engine. The engine was broken down in the weight analysis, to a very detailed level representative of the breakdown of a development engine. Also conducted at this point of the study were the aircraft and mission optimization analyses and DOC assessment, and emissions (chemical and noise) analyses, which are discussed later in this report.

Figure A-39 provides a summary of the engine material candidates. The baseline is representative of Allison's AE3007 and AE3012 engines, and the advanced engines incorporated materials of higher strength and/or lower density where they were appropriate for the environment and loads. Figure A-40 provides an indication of compressor discharge temperature (CDT) as a function of core pressure ratio, and fan pressure ratio. CDT is a key parameter in determining material requirements since is not only an indicator of the cold section maximum temperatures, but it is the source of the high pressure cooling air supply. Figure A-41 represents the weight breakdown of the final selected engines of the study, which is also representative of the information generated for the interim engines. It should be noted that for very high bypass ratio engines, as these are, fan and low pressure spool components and the nacelle are the major portion of the entire system weight. They dominate the focus of material requirements for a future (high bypass) system, and the core engine components have relatively much less impact to the overall system weight. This is an important fact, however, it must be recognized that this observation is with respect to weight only, and that some advanced core engine materials are required to achieve the core hot section temperatures and cold section pressure ratios and temperatures desired. In other words, materials for the advancement of the Brayton cycle, that is, materials that allow increase in RIT and OPR are of significant importance in the engine core, whereas materials that lend themselves primarily for weight reduction, by way of lower density, are important in the LP spool of the engine and in the nacelle.

The results of the engine weight analysis, in terms of the baseline and advanced engine parametric assessment, is shown in Figure A-42. It is interesting to note how relatively flat the weight characteristic is for the advanced engine parametric. This is primarily driven by the fact that to obtain a given thrust level the total flow requirement and thus the fan size is relatively constant and since the engine's weight is driven primarily by the LP spool system (size) for these high bypass engines, the result is this relatively flat characteristic. The domination of the LP spool relative to the core is even more pronounced as technology advances and the core becomes smaller.

3.4 Emissions (Chemical and Noise)
The assessment of technology payoff is generally a trade-off of performance, weight, and cost factors. The means to determine the relative importance of one of these parameters versus the others is generally to determine their relative impact on the aircraft system TOGW or DOC. Emissions factors such as NOx or acoustic db levels, for example, don't enter the equation of aircraft TOGW and/or DOC except from a negative impact such as weight and cost increase (i.e. there is no quantitative factor with respect to emissions that results in a benefit to TOGW or DOC). Therefore these related technologies were not ranked in the same TOGW and DOC

evaluation process as other technologies, but instead were assumed to be required to satisfy standards that would otherwise "ground" the aircraft.

Figure A-43 provides a summary of the NASA AST goals, which were treated as requirements, for this study, as well as the impact that those requirements have. The chemical emissions requirement stated as a 70% reduction of NOx emissions (relative to current ICAO regulation), can be achieved, but it does demand the use of more complex combustion systems. Allison has had experience in the assessment of several low emissions combustion system concepts (see Figure A-44), and for this effort quickly focused on a multistaged system under study at Allison known as the LDI (Lean Direct Injection) combustor (Figure A-45). The chemical emissions goals, in terms of NOx, the dominant factor, are shown in Figure A-46 along with a variety of today's engines in the background. Included is the current ICAO regulation level and a 70% reduction curve (the NASA AST goal). Also shown are the engines analyzed for this study. The -1A2 represents the baseline and is shown with a current technology, conventional, single zone combustor. The -2A2 and -3A2 represent the two advanced engines that were analyzed with the LDI combustor concept. The lower pressure ratio advanced engine (-3A2) was also assessed with a conventional combustor. Although an optimized conventional combustor for these engines could maintain a good margin against today's ICAO regulation, the advanced LDI concept is required to meet the AST goals. Having shown that the goal can be met or exceeded, the challenge then becomes one of minimizing cost of the LDI concept. Allison has identified low emissions combustor affordability development as a primary need for the AST initiative.

As stated above, acoustic emissions or noise goals were also treated as requirements. The requirement, stated as a 6-7db reduction of effective perceived noise level or EPNL (relative to FAR Part 36, Stage 3), can be achieved, but it does result in a compromise to performance and cost. A preliminary noise assessment was conducted on the selected study engines. Figure A-47 is a summary of relevant noise information from the analysis on the baseline and both advanced engine options. Furthermore analysis was conducted on higher FPR derivatives of the preferred advanced engine to quantify the impact of increased FPR on noise. Also shown on the figure is the FAR Part36, Stage 3 regulation and a summary section of deltas from that regulation. As can be seen, all three engines initially assessed with a 1.4 FPR had similar noise levels ranging from approximately 4.5 to 9 db below regulation, depending on the specific noise condition, with an accumulated noise level of approximately 21db below Stage 3 regulation. The approach condition was the most critical. Within the FAR rules of noise assessment, which allows some amount of trade-off between one noise condition and another to reach an overall level, these engines satisfy the 6-7db reduction goal. However, these margins are penalized quickly as FPR increases as shown by the last two columns on the figure. These noise assessed points are highlighted in Figures A-48 & A-49 showing their relation to the engine cycle optimization process. The curves show that a 1.4 FPR is near optimum for mission fuel burn, but that a higher FPR would be desired to minimize aircraft TOGW, which is a more indicative parameter to overall payoff. Those reductions in TOGW for increased FPR, however, come with a significant noise penalty. These curves showed the trends of FPR with fixed core compressors. Later in this report (Figures A-70 & A-71 for example) a similar trend for FPR at fixed optimum OPR is presented (without the constraint of fixed core compressors) and the result is an even greater potential payoff for increasing FPR. Since it was not in the scope of this study to complete detailed assessments of the noise reduction technologies and options, a FPR of 1.4 was selected to assure compliance with noise requirements. Allison has identified low noise fan technologies

and follow-on FPR versus noise trade-off assessment programs as another primary need for the AST initiative.

3.5 Aircraft and Mission Optimization Analysis

Ultimately technology worth has to be defined in terms of payoff to the end product, which for this study was aircraft TOGW, MFB and DOC. To translate engine impacts (fuel consumption, weight and cost) into aircraft impacts a reference mission and aircraft was defined and then sensitivities of optimized aircraft TOGW and MFB to engine fuel consumption and weight were established. Using these sensitivity factors then the technologies were assessed in terms of delta-TOGW and delta-MFB relative to the reference. Though these technologies may impact the final system (TOGW, MFB, etc.) significantly, they tend to have little impact on the sensitivity factors. In other words, regardless of how precisely we define the reference aircraft and what technology level we assume for the aircraft, we still are focusing on a certain class of aircraft and a certain overall design mission, therefore the sensitivity factors tend to be similar.

Allison initially conducted a preliminary aircraft and mission optimization based on one of the initially selected advanced engines coupled with conventional, current technology, aircraft assumptions. The aircraft optimization was based on minimizing TOGW. The result was a 120 passenger aircraft with a design range of 1500NM. From this reference sensitivity factors were established. Under separate contract to NASA, in an effort paralleling this study, McDonnell Douglas Aerospace-West (MDA-W) was utilizing our study engines and conducting their own aircraft and mission optimization analyses. Their reference was an advanced technology aircraft, and thus they focused on a 150 passenger, 2500NM design range for the same engine thrust class. Allison then utilized aircraft design assumptions consistent with the MDA-W study aircraft and updated our study. Our results including the sensitivity factors were essentially the same as MDA's, and furthermore the sensitivity factors of the final aircraft were very similar to the sensitivity factors of our initial study aircraft.

The results of the final aircraft optimization and mission assessment are summarized in Figure A-50. The aircraft is a 150000# TOGW class, two engine, under-wing design, carrying 150 passengers for a design range of 2500NM, with a design cruise speed of 0.78 Mach. The sensitivity factors were established using this reference aircraft, but for a 500NM mission which better represents typical usage of this type of aircraft. They are represented (Figure A-51) in terms of a change in aircraft TOGW and MFB for given changes in engine SFC and Thrust-to-Weight ratio (FN/WGT). Since these sensitivity characteristics are essentially linear they can be represented as a constant (with units of % per %) for each factor (i.e. a 1% change in engine weighted SFC results in a 0.3% change in optimized aircraft TOGW and a 1.0% change in MFB, while a 1% change in engine weight results in a 0.2% change in TOGW and a 0.1% change in MFB).

3.6 DOC Assessment and Sensitivity Analysis

The DOC sensitivity analysis takes the aircraft and mission analysis another step and includes all the cost elements of the system (Figure A-52). Although more complex, it is a similar process to the aircraft and mission optimization analysis in that a reference model is created and then sensitivity factors are established. In addition to the engine SFC and weight factors, DOC sensitivities must also be generated for engine acquisition cost, engine maintenance cost and aircraft acquisition cost (as it is impacted by the engine). Two fundamentally different acquisition cost groundrules can be applied to a DOC assessment, a "market" based and a "delta-

cost" based approach. The NASA groundrules for DOC assessment requested the market-based approach. Since the two approaches can lead to significantly different results, Allison conducted the analyses with both methods. A cost-based method determines the acquisition cost of the aircraft and the engine based on the estimated cost to manufacture the products. A market-based assessment determines the acquisition cost based on the estimated price the market will bare for the product, which is a primarily a function of capability and not a function of cost to manufacture. The engine's "capability" is essentially it's power or thrust delivered to the aircraft and the aircraft "capability" is it's payload (number of passengers) and range. Since this study was based on a fixed passenger load and design range, which in turn essentially requires a given thrust class engine, the acquisition cost element of DOC would be nearly fixed (or have minimal variation) and thus the DOC impact for improved technology is diluted. Since we recognize that this subject matter has resulted in long debates over which method is appropriate for technology assessment studies, we decided it was necessary to assess both methods so that the full DOC potential can be realized and the sensitivity to which method is used can also be determined.

A wide variety of factors influence the overall aircraft system cost and therefore enter the DOC assessment (Figure A-53). Many of those, however, are assumed to be constant for a given type system. For this study those constants were defined by NASA in coordination with study subcontractors and industry in general. These include items such as aircraft utilization, fuel prices, labor rates, airport fees, spares availability, and financing and insurance factors. They have been included as reference document 1 of this report.

It is worth noting the relative importance of certain elements of DOC (see Figure A-54, provided by the MDA-W study). From an overall viewpoint, the cost of ownership is about 43% of the total DOC, maintenance is about 17% and fuel is about 13%, while the remaining elements held essentially constant in this study are worth the balance of about 23%. The engine price is approximately 10% of the aircraft total price and the engine maintenance is approximately 35-40% of the total maintenance cost. Therefore the approximate factors directly effected by the engine are engine cost (~4%), engine maintenance (~6%), and fuel burn (~13%), however the engine weight and fuel burn impact the overall aircraft size (TOGW) which is related to the aircraft acquisition cost (~39%).

Engine weight and performance, as it impacts the aircraft system size and thus cost, and fuel burn are significant elements of the DOC assessment and have been discussed in previous sections of this report. The direct cost factors (acquisition and maintenance) , as they are impacted by the technologies, are clearly the other major portion of the DOC assessment.

The reference (study value) engine acquisition cost for the baseline engine is shown in Figure A-55. Also shown is the breakdown at the engine modular level and each module's percent of total. Each technology introduced into the advanced engines was assessed with respect to it's impact on acquisition cost of each engine module/component. These impacts were assessed for a fixed size component, as shown in the figure, to show the first order impact. As technologies are introduced and engine performance improvements increase, the engine size and thus the component sizes can be reduced to deliver a given thrust. These size factors or adjustments were accounted for but are not included in Figure A-55.

The reference engine maintenance cost for the baseline engine is summarized in Figure A-56, which shows the total maintenance cost (101. $/EFH) and its breakdown at the engine modular

level. Each technology introduced into the advanced engines was assessed with respect to it's impact on maintenance factors (such as frequency of inspections required, engine removal rate, component/module repair or replacement rate, material and labor cost to repair or replace, etc.). This information was assessed and expressed in terms of delta-cost (or %delta-cost) to the impacted module/component. This is also summarized in Figure A-56.

As discussed earlier in this section the DOC sensitivities are the information required to translate engine (and individual technologies) performance, weight, and cost impacts into DOC impacts. Figure A-57 is a graphical representation of the DOC sensitivity to engine SFC and weight (or thrust-to-weight ratio), and Figure A-58 is a summary of DOC sensitivity constants for each of the key, engine driven, contributing elements. These sensitivity factors are expressed as the amount of change in DOC (in percent) for a +1% change in the sensitivity parameter. At first glance these values may appear small, however, one must realize that very small percentage changes in DOC values yield significant market payback and airframers and airlines strive for tenths of a percent in DOC reduction.

3.7 Final Parametrics and Engine Selections:
The last section discussed the aircraft and mission analysis and the DOC assessment that was required to translate engine parameters into system level parameters. This section now discusses the final engine parametric study and engine selections relative to these system level parameters of interest. (Figure A-59 and A-60)

Figure A-61 thru A-64 summarize the parametric results of MFB, TOGW, DOC market-based, and DOC cost-based, represented as a function of OPR and RIT for a fixed FPR of 1.4. Figures A-65 thru A-68 repeat this set of plots for a FPR of 1.8. These figures show baseline and advanced technology levels. Also note that the three engines analyzed in more detail, as discussed in previous sections, are highlighted on the figures. The primary conclusions drawn from these figures was that the optimum RIT (max takeoff rating) was about 2400°F for the baseline technology and about 2900°F for the advanced technology engines. Furthermore a logical choice of OPR would be about 20-30 for the baseline technology and about 37-50 for the advanced technology engines. These figures clearly show the overall benefits the advanced technology engines offer over the baseline technology, and also that the PD577-2A6 option (as previously described and discussed) was a very good advanced engine solution.

As was discussed in a previous section, a FPR of 1.4 was selected to satisfy noise requirements. Figures A-69 thru A-72 show a similar set of parameters as discussed above (for constant FPR), but now holding OPR at the desired levels for each technology and varying FPR. It can be seen that there is additional benefit in TOGW and DOC at higher FPR than 1.4. These potential benefits however, come at an increased risk to satisfying future anticipated noise requirements. For this study the 1.4 FPR was selected as a good compromise. As further advancements in noise reduction and abatement technologies continue, it is entirely possible that higher FPR may be desired to take advantage of the DOC benefits. It would obviously be a trade-off of the performance benefit of the increased FPR and the cost impact of the emission reduction technology. That subject matter warrants a study in itself and was far beyond the scope of this study contract.

Additional information is provided in Figures A-73 thru A-75, which depict the trends of SFC, BPR, and engine weight with FPR. As can be seen the primary benefit to increased FPR is

reduced BPR and weight of the resulting engines, but it does come at the sacrifice of fuel consumption.

The accumulation of all of the information discussed to this point led to the selection of the advanced engine (PD577-2A6). The technologies comprising this engine are highlighted in Figure A-76, while Figure A-77 displays a summary comparison of the selected advanced engine and the selected baseline engine. Figure A-78 displays a cross-section of the advanced engine and highlights key performance parameters.

Also provided (Figures A-79 thru A-85) are some summarized details of the component designs and design substantiation (comparisons, guidelines or philosophies) for the advanced engine. It is not the intent of this report to discuss this in detail, but simply to provide this information for reference and to show that the advanced engine components satisfy reasonable design assumptions for advanced engines, and that no basic fundamentals have been violated.

3.8 Individual Technology Assessments

Section 3.2 and 3.7 discussed the parametric assessment process used to define the regions of solutions and the selection of the baseline and advanced technology engines for this study. Section 3.1 discussed the performance impact on the engine components of each of the technologies comprising the advanced engine and section 3.6 provided the cost related impacts of the technologies. This section then brings together the information from these other sections and discusses how each technology impacts the engine cycle optimization/selection and the relative payoff of the technologies.

To assess individual technologies each one was introduced one step at a time. For each incremental step the parametric process was repeated to determine the optimum engine cycle parameters (such as OPR and RIT) and also the payoff parameters (SFC, FN/Wgt, MFB, DOC). This process was repeated incrementally adding additional technologies until all the steps from the baseline to the advanced engine were defined. Furthermore this entire process was iterated to get the larger payoff (DOC) technology items in the earlier steps (Figures A-86 thru A-87).

Figures A-88 thru A-93 display the resulting parameter impact trends with each incremental technology step defined. It is evident that the various technologies have different payoff aspects. For example, the advanced materials (such as OMC) had a significant weight impact both on the engine and on TOGW but little impact on mission fuel burn. Other technologies had less weight impact but contributed more to performance improvement and/or fuel burn impact.

With DOC as the defined figure of merit it became evident that those technologies that had an impact by reducing engine secondary flows (cooling, leakage, etc.) were of most significance. Secondary flow reduction is obtained a number of ways, including better sealing technologies, increased hot section material temperature capability (advanced single crystal materials), and improved airfoil cooling effectiveness (such as advanced Castcool®/Lamilloy®). Continued research and development in component performance (efficiency @ SM, loading) improvement also shows that potential for significant payoff still exists. The reader is referred to section 3.1 for a review of these technologies, if desired. Also of significant impact was reduced nacelle drag, although this was not a focus of this study. Continued development of laminar flow nacelles has a very worthwhile payoff, assuming the various technologies can be incorporated while maintaining nacelle cost to within ~10-15% of baseline nacelle costs.

3.9 Supplemental Risk Assessment

Risk assessment is a subject matter that means different things to many people. As a result there have been many different assessment processes documented, many of which attempt to go beyond the simple qualitative (red, yellow, green) allocations historically often used. In the most classical quantitative form a risk assessment assesses probability and consequence of an event. However, these models are really only applicable to relative mature programs when these factors can be quantified with a fair amount of confidence and substantiation. When attempting to apply this type of model to advanced technology studies for not yet defined systems the quality of the model quickly deteriorates since the factors are not much more than judgement calls.

Most assessments ultimately end up using simple approaches and attempt to replace simple scales (low, medium and high, for example) with finer increments of scoring such as 1 - 10 with various attempts at defining the scale to adapt to the system under study. Furthermore some models have separate scales for cost, schedule, and technical risk with various methods to interrelate and combine them into an overall rating. As mentioned above some models express the scales in terms of probability of an event (failure) and consequence of the event. However, all of these methods still require a "judgement" by the evaluator (or hopefully evaluation team) as to where on the various scales the item being assessed belongs.

The closer to the actual product phase of the program the system is, the more meaning the risk assessment has, because the factors are better defined and more quantifiable with less judgement involved. At these higher phases of a program, such as production or even EMD, the "probability of failure events" (e.g. cost overrun, schedule slip, or technical failure), and the consequence of these failures are fairly well defined. However, for future technology assessment, when the product is barely in the conceptual stage, these risk assessment techniques become very weak. The evaluator(s) is ultimately assessing the feasibility and duration for a technology maturation. Realize that by definition of this study the technology timeframe or technology availability date (TAD) is a given, so that only those technologies that are assessed or assumed to meet that requirement are included in the study. That has already, in a sense, defined a level of allowable risk. Furthermore, by definition, the technology (and any other impacted elements of the product) is assumed to be designed and incorporated in such a way that the product requirements (such as performance, durability/life) are still satisfied. Thus another element of risk has been reduced by definition. On the other hand, a contrasting viewpoint would be that all "advanced" technologies are high risk because of the lack of available information to substantiate otherwise.

With the above said, the assessment of risk of each technology (for this type of future concept study) reduces to an assessment of it's maturity relative to the required TAD and an assessment of the accuracy of the assumed cost impact to the product. For this study the cost and maturity assessments were based on the collective input from the "experts" within Allison including whatever industry data they had available to them.

It was anticipated, for this study (and in general this type of study), that all technologies would fall into a rather narrow band (essentially depending on how far away the assessed TAD was for each technology. With a year 2005 EIS the TAD requirement is defined at about year 2001, which puts technology demonstrations in the 1997-1998 timeframe, or essentially in the next few

years, which means that most technology candidates for this study have some R&D behind them already.

In an attempt to apply a structured assessment a simplified version of an established and documented method was used. (See Figure A-49.) This method in it's original form was developed by the "Defense Systems Management College" and was published in the "Systems Engineering Management Guidelines". It considers both technical and cost risk. It was simplified by having the technical risk factors be represented by the assessed development time required (assuming available resources) to mature the technology to production readiness, on a 1-4 relative scale as follows:

Risk Level 1 - minimal risk, the technology is within a year of production readiness (EIS).
Risk Level 2 - low risk, 2-3 years of development required for production readiness.
Risk Level 3 - medium risk, 4-6 years of development required for production readiness.
Risk Level 4 - high risk, 7+ years of development required for production readiness.

Figure A-95 summarizes the risk assessment for the high priority technology items.

The primary conclusion from this simplified risk assessment is as was anticipated. All items fall within a relatively narrow band because they are all "advanced" technologies, and they all have some R&D, basic concept, experience with which to draw from. A more in-depth risk assessment (beyond the scope of the simplified one in this study contract) would provide more benefit in conjunction with follow-on programs for each of the key technology areas.

3.10 Conclusions and Summary
Overall results of the study, such as the benefits of the advanced technology engine relative to the baseline, a summary of the advanced technology engine, and the resulting critical technology needs, were provided in the Executive Summary, Section 1. Some additional conclusions drawn from the study are outlined in Figures A96-A99.

- Future anticipated emissions (chemical and noise) requirements (see section 3.4) can be met if appropriately addressed. They do require a combustion system of higher complexity than today's systems and furthermore may require a fan design that compromises performance and weight somewhat relative to what would be desired for performance alone.

- The higher overall pressure ratio of advanced technology engines will require materials development for the compressor component rear stages due to the increased temperature, the need to design for creep-fatigue interaction, and the desire for light weight.

- Candidate component materials were prioritized essentially by the relative weight of the candidate components to the overall engine. Since the fan and fan, and fan case, components are such a high portion of the overall engine weight (especially with these high bypass ratio engines), the OMC/PMC materials are of primary importance. TiAl and MMC also offer positive payoffs but much less so simply because their candidate components are a much smaller portion of the overall engine weight.

- Desired engine overall pressure ratio and turbine inlet temperature increased from a baseline level of about 25-30 and 2400-2600°F, respectively to around 40 and about 2900-3000°F via the incorporation of advanced technologies. The core compressor pressure ratio increased from about 20 for the baseline to about 25-30 for the advanced technology engine. This "fits" well with a family (and growth) plan for Allison, whereby the AE3012 engine, in a modern technology 12000# thrust class turbofan, with it's 20/1 class pressure ratio core compressor can be grown and matured to a future (technology) engine with a higher RIT and a 30-35/1 core compressor producing a 25000-30000# thrust class engine (AE302X) for the 2005 timeframe. Furthermore this can be accomplished by zero-staging a developed version of the baseline compressor (same flowpath) and utilizing the same flowsize (flowpath) hot section. Figure A-99 displays this concept. The 25000# thrust class version could use the same core compressor and turbine flowpath with a supercharging stage in front of the HP compressor and an increased combustor temperature rise (higher RIT).

- Figure A-100 summarizes the technologies in a prioritized list. Recognize (as discussed in section 3.4) that the Low NOx Combustor and the low noise fan are placed in prioritization rank by the necessity to meet future anticipated emission requirements. The remainder of the technologies are ranked using DOC as the figure of merit. Figure A-101 shows the high priority technology needs expressed in terms of candidate technology development programs. These program needs establish the cornerstone of Allison's proposed focus for NASA's AST initiative.

TABLE 1 - INCREMENTAL TECHNOLOGY IMPACT SUMMARY

|	Base	LOW NOx COMB STEP-1	DELTA	CASTCOOL STEP-2	DELTA	SEALS/DISK STEP-3	DELTA	Low Noise Fan STEP-4	DELTA	CMSX10 STEP-5	DELTA
Net Component Level Impact											
Fan Hub Eff-a	0.901	0.901		0.901		0.901		0.901		0.900	-0.0
Fab Tip Eff-a	0.901	0.901		0.901		0.901		0.901		0.900	-0.0
PRtip	1.40	1.40		1.40		1.40		1.40		1.40	
Eff-p Overall	0.905	0.905		0.905		0.905		0.905		0.905	
HPC Eff-a	0.858	0.858		0.842	-1.6	0.840	-0.3	0.840		0.836	-0.3
WinCORRex (Exit Corrected Inlet Flow)	8.43	8.43		4.72	-44.0%	4.34	-7.9%	4.34		3.82	-12.0%
PR/Stg	1.22	1.22		1.22		1.22		1.22		1.22	
Eff-p	0.901	0.901		0.896	-0.5	0.896	-0.1	0.896		0.894	-0.1
HPT Eff-a	0.894	0.894		0.888	-0.7	0.886	-0.1	0.886		0.885	-0.2
WCORRin (Inlet Equivalent Flow)	12.58	12.58		6.80	-45.9%	6.32	-7.0%	6.32		5.64	-10.8%
LPT Eff-a	0.925	0.925		0.923	-0.2	0.923	-0.1	0.923		0.922	-0.1
WCORRin (Inlet Equivalent Flow)	43.9	43.9		30.0	-31.6%	28.2	-6.2%	28.2		24.9	-11.8%
Leakage / Purge Flows	5.29	5.29		5.29		2.97	-2.3	2.97		2.97	
Chargeable Turbine Cooling	7.98	7.98		11.62	3.6	12.03	0.4	12.03		11.41	-0.6
Effectivness (Tg-Tm)/(Tg-Tc)	0.53	0.53		0.67	27.9%	0.68	1.7%	0.68		0.67	-2.6%
RIT (CERT)	3060	3060		3460	13.1%	3460		3460		3560	2.9%
CDT (CERT)	1273	1273		1468	15.3%	1502	2.3%	1502		1535	2.2%
Tm (for Desn Life)	2120	2120		2120		2120		2120		2210	4.2%
Total Chargeable Cooling	13.27	13.27		16.91	3.6	15.00	-1.9	15.00		14.38	-0.6
Net Cycle/Engine Level Impact											
RIT (Max Rated T/O)	2860	2860		3260	14.0%	3260		3260		3360	3.1%
OPR	20.3	20.3		32.2	58.3%	34.7	7.7%	34.7		37.1	7.1%
BPR	12.1	12.1		15.4	26.7%	15.8	2.4%	15.8		17.1	8.7%
WATc	1404	1404		1445	2.9%	1448	0.2%	1448		1460	0.8%
WHPCc	89.4	89.4		73.8	-17.5%	72.3	-2.0%	72.3		67.4	-6.8%
Weight	9664	9664		9614	-0.5%	9587	-0.3%	9587	*	9564	-0.2%
FN/Wgt @ Climb	0.48	0.48		0.48	-0.4%	0.48	0.4%	0.48	*	0.48	-0.2%
SFC @ Climb	0.629	0.629		0.599	-4.8%	0.591	-1.4%	0.591		0.584	-1.2%
SFC @ Cruise	0.633	0.633		0.602	-4.8%	0.594	-1.4%	0.594		0.586	-1.3%
SFC - Weighted	0.632	0.632		0.601	-4.8%	0.593	-1.4%	0.593	*	0.585	-1.3%
Maintenance Cost (Rel. to Base)	0.0	0.5	0.5	1.3	0.8	5.0	3.7	5.0	*	6.6	1.6
Rel. Acquisition Cost (Delta-Based)	0.0	1.0	1.0	-14.9	-15.9	-13.9	1.0	-13.9	*	-16.0	-2.1
Noise (Accum. Rel. to FAR-Part36,Stg3)	-21	-21	0	-21		-21		-21	*	-21	
Chemical Emissions (NOx Rel. to ICAO)	-53%	-73%	-19%								
Net Aircraft/System Level Impact								*not quantified			
Rel. TOGW	0.00	0.00		-1.53	-1.5	-2.01	-0.5	-2.01		-2.40	-0.4
Rel. MFB	0.00	0.00		-4.98	-5.0	-6.39	-1.4	-6.39		-7.65	-1.3
Rel. DOC (Delta-Cost Based)	0.00	0.09	0.1	-2.59	-2.7	-2.72	-0.1	-2.72	*	-3.19	-0.5
Rel. DOC (Market Based)	0.00	0.00		-0.64	-0.6	-0.80	-0.2	-0.80	*	-0.95	-0.2
Forced Ranking	0	1		2		3		4		5	

TABLE 1 - INCREMENTAL TECHNOLOGY IMPACT SUMMARY

	COMPONENT EFF.		LD NACELLE		OMC		MMC		TIAL		OTHER		ADVANCED
Net Component Level Impact	STEP-6	DELTA	STEP-7	DELTA	STEP-8	DELTA	STEP-9	DELTA	STEP-10	DELTA	STEP-11	DELTA	VS. Base
Fan Hub Eff-a	0.906	0.5	0.906		0.906		0.906		0.906		0.906		0.5
Fab Tip Eff-a	0.906	0.5	0.906		0.906		0.906		0.906		0.906		0.5
PRtip	1.40		1.40		1.40		1.40		1.40		1.40		
Eff-p Overall	0.91	0.5	0.91		0.91		0.91		0.91		0.91		0.5
HPC Eff-a	0.849	1.3	0.849	-0.1	0.849		0.849		0.849		0.849		-0.9
WinCORRex (Exit Corrected Inlet Flow)	3.57	-6.7%	3.48	-2.5%	3.48		3.48		3.48		3.48		-58.8%
PR/Stg	1.22		1.40	14.8%	1.40		1.40		1.40		1.40		14.8%
Eff-p	0.903	0.9	0.903	-0.0	0.903		0.903		0.903		0.903		0.2
HPT Eff-a	0.894	0.9	0.893	-0.0	0.893		0.893		0.893		0.893		-0.1
WCORRin (Inlet Equivalent Flow)	5.25	-6.9%	5.12	-2.6%	5.12		5.12		5.12		5.12		-59.3%
LPT Eff-a	0.931	1.0	0.931	-0.0	0.931		0.931		0.931		0.931		0.6
WCORRin (Inlet Equivalent Flow)	23.2	-6.5%	22.7	-2.3%	22.7		22.7		22.7		22.7		-48.4%
Leakage / Purge Flows	2.97		2.97		2.97		2.97		2.97		2.97		-2.3
Chargeable Turbine Cooling	11.47		11.49	0.0	11.49		11.49		11.49		11.49		3.5
Effectivness $(T_g-T_m)/(T_g-T_c)$	0.67	0.1	0.67		0.67		0.67		0.67		0.67		27.1%
RIT (CERT)	3560	0.3%	3560	0.0%	3560		3560		3560		3560		16.3%
CDT (CERT)	1541		1541		1541		1541		1541		1541		21.1%
Tm (for Desn Life)	2210	0.4%	2210		2210		2210		2210		2210		4.2%
Total Chargeable Cooling	14.44	0.1	14.46	0.0	14.46		14.46		14.46		14.46		1.2
Net Cycle/Engine Level Impact													
RIT (Max Rated T/O)	3360		3360		3360		3360		3360		3360		17.5%
OPR	39.0	5.0%	39.0		39.0		39.0		39.0		39.0		91.8%
BPR	17.6	2.9%	17.6	-0.1%	17.6		17.6		17.6		17.6		45.0%
WATc	1467	0.5%	1428	-2.6%	1428		1428		1428		1428		1.7%
WHPCc	65.9	-2.3%	64.2	-2.5%	64.2		64.2		64.2		64.2		-28.1%
Weight	9518	-0.5%	9403	-1.2%	8404	-10.6%	8371	-0.4%	8095	-3.3%	7767	-4.1%	-19.6%
FN/Wgt @ Climb	0.48	0.6%	0.49	1.5%	0.55	11.9%	0.55	0.4%	0.57	3.5%	0.59	4.4%	23.5%
SFC @ Climb	0.568	-2.7%	0.552	-2.8%	0.552		0.552		0.552		0.552	-0.0%	-12.3%
SFC @ Cruise	0.570	-2.7%	0.553	-3.0%	0.553		0.553		0.553		0.553	0.0%	-12.6%
SFC - Weighted	0.569	-2.7%	0.553	-3.0%	0.553		0.553		0.553		0.553	0.0%	-12.5%
Maintenance Cost (Rel. to Base)	9.8	3.2	11.0	1.2	11.6	0.6	11.8	0.2	15.5	3.7	15.5		15.5
Rel. Acquisition Cost (Delta-Based)	-15.8	0.2	-15.0	0.8	-12.0	3.0	-11.3	0.7	-9.2	2.1	-9.2		-9.2
Noise (Accum. Rel. to FAR-Part36,Stg3)	-21		-21		-21		-21		-21		-21		0
Chemical Emissions (NOx Rel. to ICAO)											-73%		-19%
Net Aircraft/System Level Impact													
Rel. TOGW	-3.31	-0.9	-4.42	-1.1	-6.35	-1.9	-6.42	-0.1	-7.05	-0.6	-7.88	-0.8	-7.9
Rel. MFB	-10.29	-2.6	-13.19	-2.9	-14.28	-1.1	-14.32	-0.0	-14.67	-0.4	-15.14	-0.5	-15.1
Rel. DOC (Delta-Cost Based)	-3.67	-0.5	-4.16	-0.5	-4.44	-0.3	-4.39	0.1	-4.33	0.1	-4.59	-0.3	-4.6
Rel. DOC (Market Based)	-1.28	-0.3	-1.67	-0.4	-1.94	-0.3	-1.95	-0.0	-2.01	-0.1	-2.12	-0.1	-2.1
Forced Ranking	6		7		8		9		10		11		

CHART 1
NASA ASTEA - Technology Impact Summary
(Allison / NASA Contract NAS3-25459, Task 7)
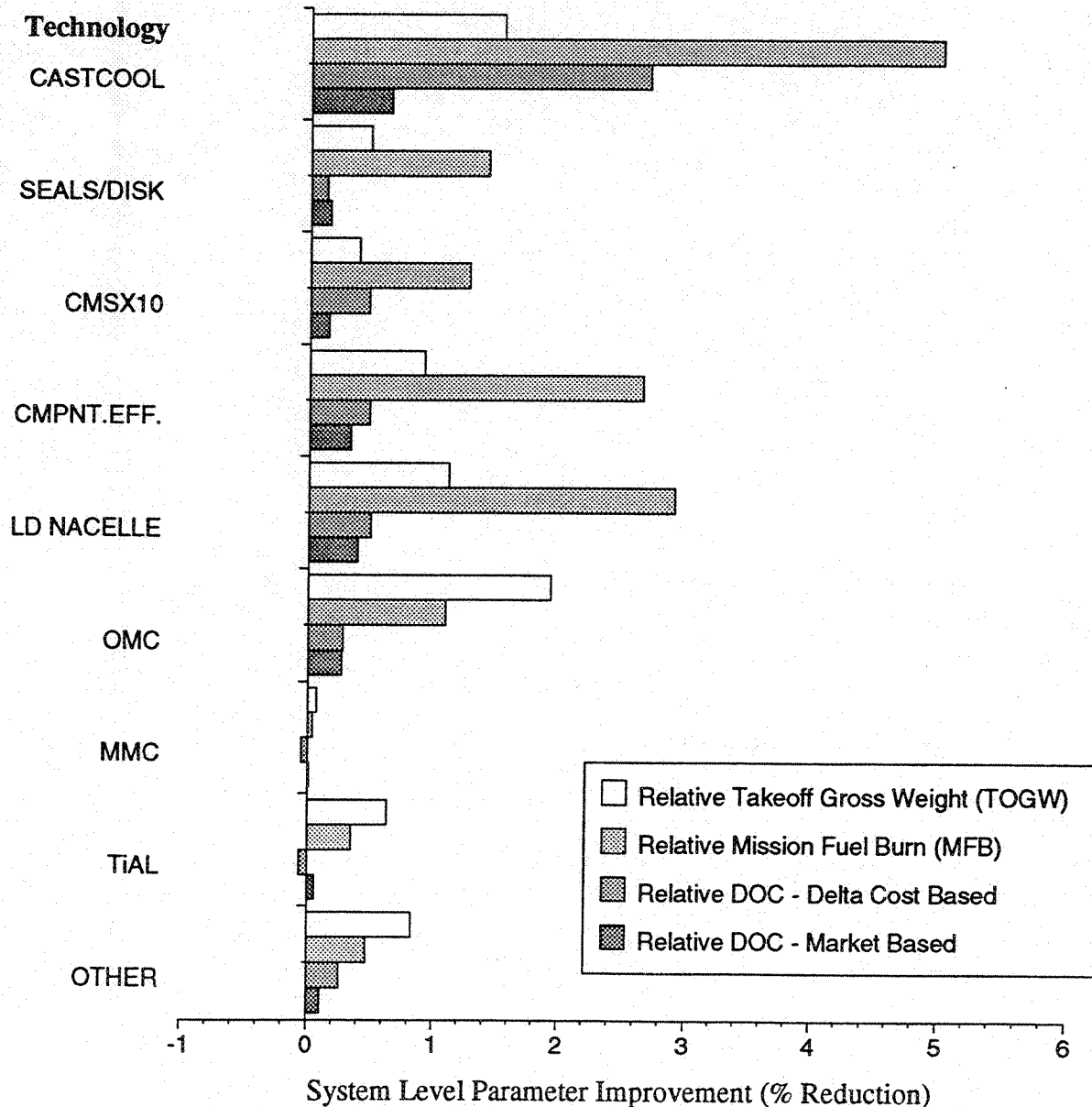
MODIFIED DIRECT OPERATING COST + INTEREST GROUND RULES FOR ADVANCED SUBSONIC AIRCRAFT

(6/8/94)

ITEM	100 - 150 PAX	200 - 300 PAX (Two Class)	600+ PAX (Three Class)
COST YEAR DOLLARS	1993$	1993$	1993$
TYPE OF OPERATION	DOMESTIC	INTERNATIONAL	INTERNATIONAL
ANNUAL UTILIZATION, TRIPS/YR	2120	600	480
STAGE LENGTH, NMI	500	3000	4000
WEIGHTS/CREW/PAX			
FLIGHT CREW, 2 PERSON+BAGS, LB	390	390	390
FLIGHT ATTENDANTS	1 PER 35 SEATS	1 PER 30 SEATS	1 PER 30 SEATS
PAX + BAGGAGE, LB (ASSUMES: 100% PAX loading, no cargo)	210 PER PAX	210 PER PAX	210 PER PAX
FUEL PRICE, $/GALLON	.65	.70	.70
FUEL DENSITY, LB/GALLON	6.7	6.7	6.7
MAINTENANCE			
LABOR RATE, $/HOUR	25.	25.	25.
OVERHEAD, %DIRECT LABOR	200	200	200

ITEM	100 - 150 PAX	200 - 300 PAX (Two Class)	600+ PAX (Three Class)
FLIGHT CREW COSTS, $/BLOCK HOURS	A+B*(MTOGW/1000) A=$440. B=$0.532 MTOGW - MAX TAKE-OFF GROSS WEIGHT	A+B*(MTOGW/1000) A=$482. B=$0.590 MTOGW - MAX TAKE-OFF GROSS WEIGHT	A+B*(MTOGW/1000) A=$482. B=$0.590 MTOGW - MAX TAKE-OFF GROSS WEIGHT
CABIN CREW COSTS, $/CREW BLOCK HOURS	$60.*SEATS/35	$78.*SEATS/30	$78.*SEATS/30
LANDING FEES, $ PER TRIP	$1.50*(MLDW/1000) MLDW - MAX LANDING WEIGHT	$4.25* (MTOGW/1000) MTOGW - MAX TAKE-OFF GROSS WEIGHT	$4.25* (MTOGW/1000) MTOGW - MAX TAKE-OFF GROSS WEIGHT
NAVIGATION FEES, $ PER TRIP	NONE	$0.136*OLD*SQRT(MTOGW/1000) OLD - OVERLAND DISTANCE, 500 NMI MTOGW - MAX TAKE-OFF GROSS WEIGHT	$0.136*OLD*SQRT(MTOGW/1000) OLD - OVERLAND DISTANCE, 500 NMI MTOGW - MAX TAKE-OFF GROSS WEIGHT

NOTE:
** Based on market price for airframe and engine

ITEM	100 - 150 PAX	200 - 300 PAX (Two Class)	600+ PAX (Three Class)
AIRFRAME MAINTENEANCE, $	AFMAINT	AFMAINT	AFMAINT

AFMAINT = (AFMAT+AFLAB)

Where:

AFMAT(Airframe maintenance material)
= (AFMC+AFMH*FH)*1.042

$AFMC = 15.20 + (97.33*AFW)/10^5 - 2.862*(AFW/10^5)^2$

AFW = Airframe Weight,Lbs
= Manufacturers Empty Weight - Bare Engine Weight

$AFMH = 12.39 + (29.80*AFW)/10^5 + .1806*(AFW/10^5)^2$

BH = Block Hours Per Trip

FH = Flight Hours Per Trip = BH - .25

AFLAB(Airframe Maintenance Labor)
= LABOR*(AFLC + AFLH*FH)

$AFLC = 1.614 + (.7227*AFW)/10^5 + .1024*(AFW/10^5)^2$

$AFLH = 1.260 + (1.774*AFW)/10^5 - .1071*(AFW/10^5)^2$

LABOR = Labor Rate

| ANNUAL HULL INSURANCE, % FRICE ** | .35 | .35 | .35 |

(CONTINUED)
ITEM

	100 - 150 PAX	200 - 300 PAX (Two Class)	600+ PAX (Three Class)
**DEPRECIATION **			
PERIOD, YEARS	15	15	15
RESIDUAL, % PRICE	10	10	10
**SPARES **			
AIRFRAME, % PRICE	6	6	6
BARE ENGINES, % PRICE	23	23	23
**FINANCING (INCL SPARES) **			
PERIOD, YEARS	15	15	15
AMOUNT, %	100	100	100
RATE, %	8	8	8
PAYMENTS	2 LEVEL PRINCIPAL/YEAR	2 LEVEL PRINCIPAL/YEAR	2 LEVEL PRINCIPAL/YEAR
PRODUCTION SCHEDULE			
RATE, UNITS PER MONTH	10	5	3
BASELINE NUMBER OF UNITS	500	300	200
ALTERNATE NUMBER OF UNITS	1000	500	400

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13. ABSTRACT (Maximum 200 words)

To retain a preeminent U.S. position in the aircraft industry, aircraft passenger mile costs must be reduced while at the same time, meeting anticipated more stringent environmental regulations. A significant portion of these improvements will come from the propulsion system. A technology evaluation and system analysis was accomplished under this task, including areas such as aerodynamics and materials and improved methods for obtaining low noise and emissions. Previous subsonic evaluation analyses have identified key technologies in selected components for propulsion systems for year 2015 and beyond. Based on the current economic and competitive environment, it is clear that studies with nearer turn focus that have a direct impact on the propulsion industry's next generation product are required. This study will emphasize the year 2005 entry into service time period. The objective of this study was to determine which technologies and materials offer the greatest opportunities for improving propulsion systems. The goals are twofold. The first goal is to determine an acceptable compromise between the thermodynamic operating conditions for A) best performance, and B) acceptable noise and chemical emissions. The second goal is the evaluation of performance, weight and cost of advanced materials and concepts on the direct operating cost of an advanced regional transport of comparable technology level.

14. SUBJECT TERMS

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